High Resolution Cross-Well Imaging of a West Texas Carbonate Reservoir: Part 1. Data Acquisition and Project Overview

BG1.2

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SUMMARY

Cross-well traveltime tomography and reflection imaging are combined to produce high resolution images of a West Texas carbonate reservoir. The cross-well activity is the geophysical component of a miscible flood CO_2 pilot site study. The cross-well objectives are to (1) evaluate the effectiveness of the high frequency piezoelectric source, (2) assess the capability of cross-well seismology to assist with reservoir delineation and characterization prior to CO_2 injection, and (3) monitor movement of CO_2 after injection. The pre-CO_2 results presented herein illustrate vividly how high frequency cross-well seismology can be used for high resolution imaging of velocity and bed geometry inside a thin reservoir. Moreover, the results demonstrate the great potential of cross-well seismology to meet the needs of high resolution reservoir description. Data from two cross-well profiles are described, one between wells 184 feet apart, the other between wells 600 feet apart. In this paper, Part 1 of 4, we review data acquisition and an overview of tomography and reflection processing. We discuss the hardware used, data gathering method, then summarize the results to date.

SITE DESCRIPTION

The primary target of the cross-well profiles is the Permian-aged San Andres/Grayburg formation. The depositional sequence consists of a series of upwardly shallowing and prograding carbonate units. Production is mainly from the Grayburg where several distinct depositional groups and lithofacies can be identified. Structually, the region is flat although mildly increasing dips can be found toward the bottom of the surveyed section. The dominant lithologies encountered are dolomite and anhydrite. Reservoir rocks are primarily dolomitized carbonates. Overall, the reservoir is characterized by irregular geometry and significant variations in both porosity and permeability. Average porosity throughout the field is about 10% but varies higher due to solution enhancement and lower because of evaporites. Permeability is also quite variable averaging only a few millidarcies throughout the main pay, but increasing to a few hundred millidarcies in thin high permeability streaks that can cause significant fluid channeling.

Seismic properties of the sequences are approximately known from well logs run throughout the field. Compressional wave velocities range from about 14,000 ft/sec to over 21,000 ft/sec. Density values range from slightly less than 2.6 gm/cm^3 in the reservoir to over 3 gm/cm^3. The composite reservoir zone is approximately 100 feet thick. Its thickness and large contrast (>20%) with the surrounding formations represent an easily visible target for either seismic tomography or reflection imaging.

This area of West Texas has been under production since the mid 1930s. Our particular field has undergone significant infill drilling dating back to the late 1950s when waterflood patterns were introduced. The profile area is part of three 20-acre five spot patterns in a CO_2 pilot study. An observation well, used for the cross-well profiling, was drilled for the CO_2 study. This observation well has a large suite of logs and core samples that will be used later for interpretation. The field location, reservoir depths, and names of wells have been altered for purposes of this presentation.

DATA ACQUISITION

Two cross-well profiles were run as shown in Figure 1. Well A, the observation well, was used for the receivers during both surveys. The well spacings were 184 feet and 600 feet, respectively. Profile #1 was recorded between wells A and B and consisted of nearly 36,000 traces. Profile #2, acquired between wells A and C, consisted of over 37,000 traces. Receiver positions were approximately centered about the reservoir as shown in the figure. Profile #1 was uniformly sampled at 2.5 ft. source and receiver spacing, Profile #2 at 5.0 ft.

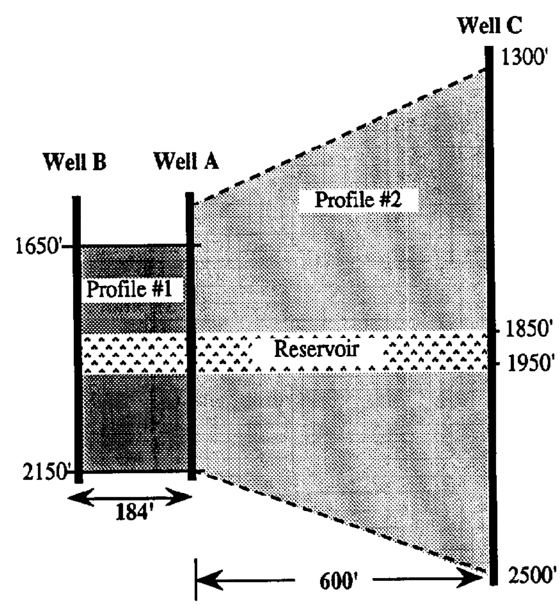

Figure 1. Profile #1 (201 sources x 178 receivers) was recorded between wells A and B. Profile #2 (240 sources x 153 receivers) was recorded between wells A and C. Receivers are in Well A.

Previously recorded high frequency "tomography" data sets were not fully suitable for reflection processing because of severe spatial aliasing of events with low phase velocity, e.g., reflected arrivals and tube waves (Rector, 1992a). Partly in response to our interest to create high resolution reflection images from cross-well data, we focused attention on improving data acquisition, namely finer sampling and faster acquisition. The West Texas profiles described here were the first run using the new acquisition method of recording on-the-fly, where the source is continuously moving while being fired. This technique significantly improved depth control and acquisition speed.

A schematic outline of Stanford's data acquisition system is shown in Figure 2. The system consists of a three-element piezoelectric downhole source, a nine-level hydrophone array, and of course, two logging trucks with associated surface equipment and instruments to control the downhole tools. A brief review of the field operations, followed by descriptions of the hardware, is given below.

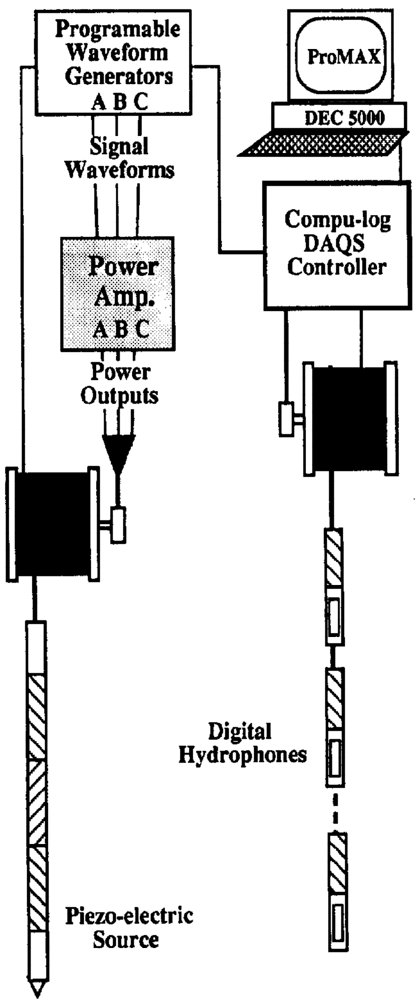

Figure 2. Diagram of the STP data acquisition system.

Field Operations

The data were acquired as common-receiver gathers or receiver fans. For each group of receiver fans, the hydrophone array (usually 7 or 8 elements) was positioned in the well and set up for recording. The source was then logged up the well at approximately 500 feet per hour. As the source moved continuously, it and the receiver would receive trigger signals from the wireline depth system at regular depth intervals. The trigger initiated the vertical stack. Profile #1 was recorded at 2.5 foot source spacing with a stack of two sweeps. Profile #2 was recorded at 5.0 source spacing with a stack of four sweeps. The major advantage of shooting "on-the-fly" was that the depth interval between shot points could be accurately maintained throughout the survey due primarily to the continuous movement of the source with the wireline under steady tension. As a result, data were collected at a rate of nearly 1400 traces per hour. Profile #1 (36,000 traces) took little more than 48 hours to complete despite some downtime for minor repairs. Profile #2 (37,000 traces) took only 40 hours to complete including time for the rig up on well C.

An identical sweep was used in both surveys, i.e., a 250-2000 Hz linear upsweep of 200 mS duration. A listen time of 300 mS and 500 mS were used for Profiles #1 and #2, respectively. The data were sampled at 200 υS with the low cut filters (-3 dB) set to 250 Hz and the high cuts at 2000 Hz. A representative common-receiver gather from each profile is shown in Figure 3.

The Piezoelectric Downhole Source

The downhole source consists of three active elements, symmetrically placed into the downhole tool to form a balanced source unit. Two banks of power transformers are mounted above and below the active transducers for symmetry. The balance is intended to reduce spurious modes of structural vibration, thus creating more radiation from desired modes. The transducers are wired as an adjacent array, capable of being driven independently for purposes of beamsteering. The elements may be operated as three independent sources or as a single unit for increased coherent output. No beamsteering was used while recording the West Texas profiles. Source signatures are generated by three 12-bit D-to-A phase-coherent waveform generators. Arbitrarily defined waveforms including sweeps, pulses, and pulse sequences can be used. The source is powered by a three-channel 24 kVA linear power amplifier. This power is delivered via a 7-conductor armored wireline. The cable has the standard 7-conductor configuration but uses lower resistance conductors and special insulation for better power transfer.

The Hydrophone Receiver System

The receiver system consists of a nine-level array of hydrophones. Each level is independently digitized downhole with sixteen bits of resolution. A surface-based computer provides control of recording parameters, including sampling rate, downhole analog and digital gain, vertical stacking depth, and high and low pass filter settings. The hydrophones are interfaced to the surface via a telemetry sonde that controls communications and data transfer. Data are stacked downhole in order to reduce transmission throughput. The entire system is run on 17, 000 feet of standard seven-conductor wireline. Recording parameters are saved to segy headers along with the trace data. Also, both downhole source and receiver depths are electronically monitored and recorded to the segy header. Finally, the data are transferred to a DEC 5000 workstation running ProMAX for correlation and in-field quality control and processing.

PROCESSING AND INTERPRETATION

Our data processing scheme combines traveltime tomography and reflection imaging as shown schematically in Figure 4. For details, the reader is referred to three companion papers in this volume: (Van Schaak, et al, 1992a), (Van Schaak, et al, 1992b), (Rector, et al,1992b), and (Lazaratos, et al, 1992). Initial results for Profile #1 are discussed below.

Results from the processing are shown in Figure 5. Tomography (Fig. 5a) provides a very good quantitative estimate of interval velocity. Van Schaack, et al (1992b) compares the velocities estimated from the tomography and the logs. Resolution is better vertically than laterally as is well known for the limited view cross-well geometry. Based on the smoothing parameters used on the logs, we estimate the vertical resolution of the cross-well velocity tomogram at about 10 feet. Overall, the tomography is extremely successful at imaging the transition zones above and below the reservoir but is less successful with the more subtle variations inside the reservoir. For example, we see excellent imaging of the sharp transition in velocity from about 20,000 ft/s above the reservoir to 16,500 ft/s inside the reservoir near the depth of 1850 feet. Similarly, below the reservoir, tomography delineates the more gradual transition out of the reservoir into faster rocks. Subtle lateral variations inside the reservoir are indicated but are not yet interpretable as geology or reconstruction artifacts. A constant velocity starting model was used to initiate the inversion results shown in Figure 5a.

The reflection image for Profile #1, shown in Figure 5b, was generated by a pre-stack XSP-CDP mapping algorithm (Lazaratos, et al, 1992). Though the reflection image is qualitative in nature, it gives 2-3 times better resolution than tomography. Wavefield separation (Rector, 1992b) plays an important part in data preparation before imaging. This method is similar to offset VSP imaging. However, XSP-CDP uses many more gathers of data and combines upgoing and downgoing reflections, in this case from over 750 gathers. The volume of data and sorts available from the cross-well geometry provide more opportunity for reflection enhancement. Reflections imaged *inside* the reservoir (1850 ft - 1950 ft) provide an unambiguous measure of bed continuity, at a vertical resolution better than 5 feet. Aside from this excellent resolution of features inside the reservoir, the image also provides other remarkable ties. See, for example, the twin features marked near 2100 feet in well A to the single feature marked in Well B. The reflection image provides the geometric guide for connecting these features, thus delineating the geological framework of the interwell region.

Unlike surface seismic, which is often displayed as a time section, cross-well reflection images are true depth images with higher spatial resolution. For comparison, we show a typical surface seismic section from the West Texas study area (Figure 5c). (Absolute times and parts of the overburden have been removed.) These data were recorded with 250-foot shot-point spacing with about 50 Hz of bandwidth (e.g., 5-55 Hz). At reservoir depth, the wavelength approaches 300 feet; therefore, the entire 100-foot thick reservoir is visible only as a single event. Reservoir structure is unresolved, that is, no separate identification of the top, bottom, or internal structure is possible. Also, the entire lateral section imaged by cross-well is less than two surface seismic CDP points wide - as illustrated. Clearly, cross-well seismology, whether tomography or reflections, offers complementary high resolution advantages to surface seismic.

CONCLUSIONS

We have shown how cross-well transmission traveltimes and reflections are combined to image the internal structure of a West Texas carbonate reservoir. The high resolution images result from the critical cooperation of new data acquisition and data processing techniques. Though at small scale, only 184 feet between wells for Profile #1, we believe our results illustrate the enormous potential of cross-well seismology to usefully address reservoir delineation and characterization problems. As illustrated in Figure 5, one role for cross-well imaging is to complement the low resolution but large coverage already available from surface seismology. Moreover, the initial results discussed for Profile #1 are only the beginning. Profile #2 has yet to be processed. Also, much work remains to be done, including processing S-wave tomograms and S-to-S reflection images from both profiles. In addition, our plans include using logs, cores, and an anticipated 3D surface survey to make quantitative estimates of reservoir properties throughout the field. We believe that these results will be extremely useful in reservoir characterization for the CO_2 injection study. A post CO_2 injection survey is planned for late 1992 to attempt monitoring.

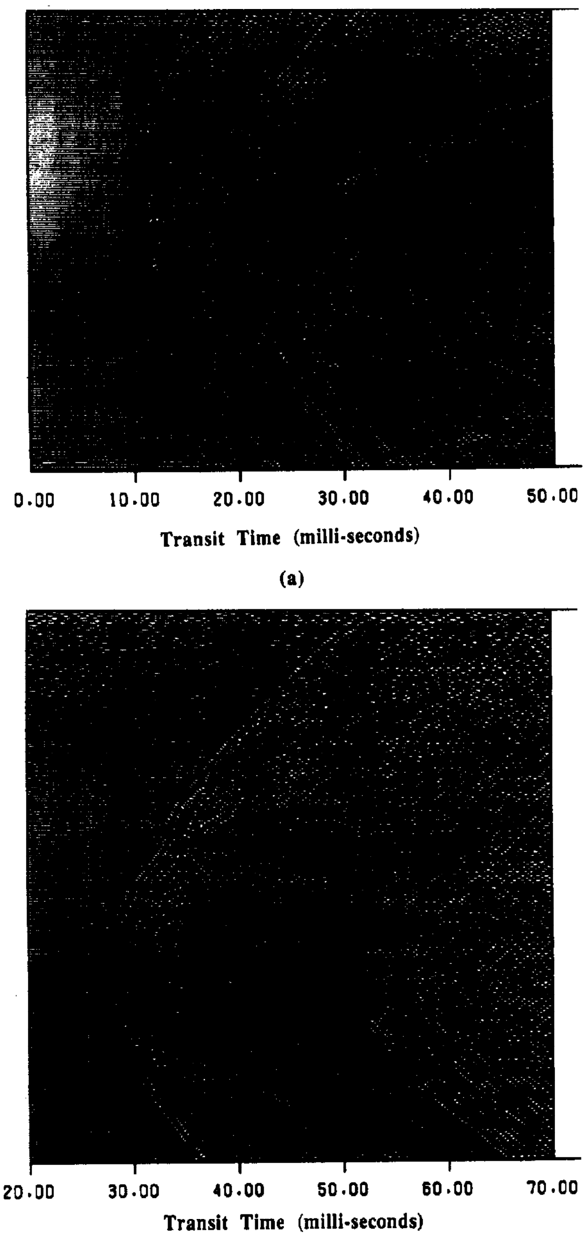

Figure 3. Common-receiver gathers: (a) Profile #1, 2.5 ft. source spacing; Wells A-B. (b) Profile #1, 5.0 ft. source spacing; Wells A-C.

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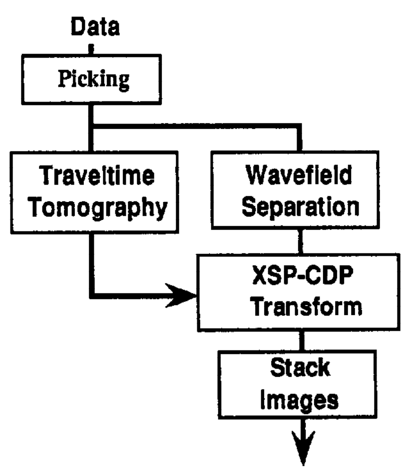


Figure 4. Schematic flow of cross-well data processing for tomography and reflections.

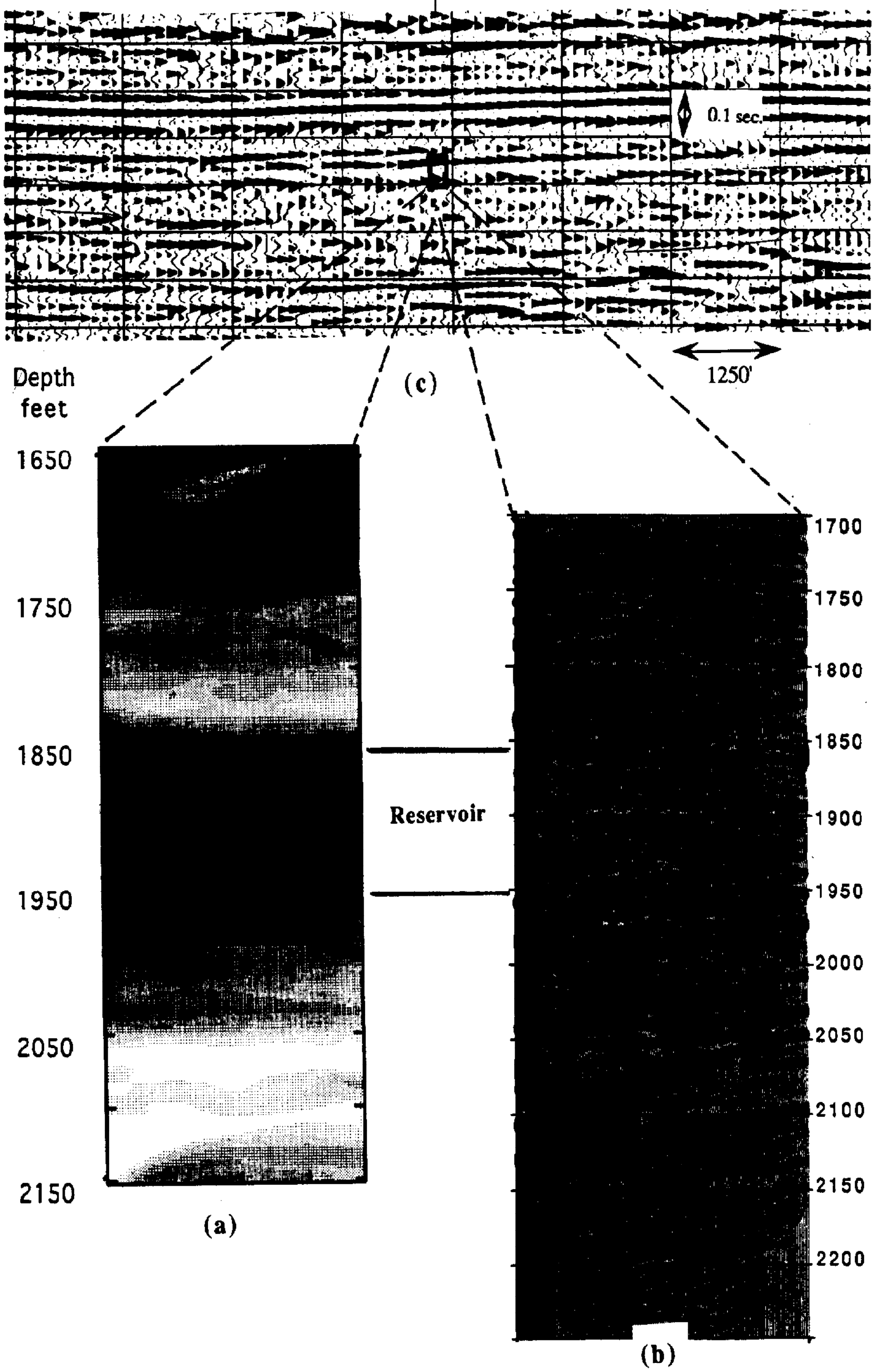
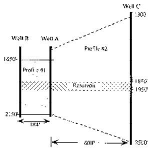
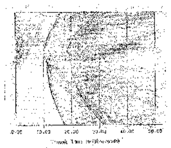


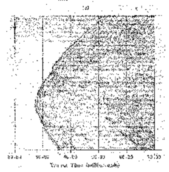
Figure 5. Complementary images of the reservoir. (a) Cross-well traveltime tomogram; (b) Cross-well P-to-P reflection image; (c) Surface seismic reflection image.



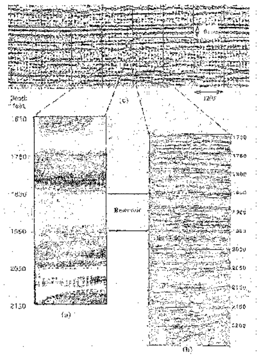
Well C
1300'
Well B
Well A
Profile #2
1650'
Profile #1
1850'
Reservoir
1950'
2150'
184'
600'
2500'



(a)



(b)



(c)
Depth
feet
1750
1950
2050
2150
(a)
Reservoir
1700
1750
1800
2000
2050
2200
(b)